CHARACTERIZATION OF HIGH ENERGY DENSITY CAPACITORS UNDER PROJECTED U.S. NAVY ETC GUN OPERATING CONDITIONS

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ABSTRACT

The US Navy has been developing ETC gun system technologies since 1990 for use in ship self defense and surface fire support missions. Emphasis has been placed on the capacitor-based pulse forming network (PFN) as the primary means of energy storage and pulse shaping. Defining and understanding the electrical and mechanical performance characteristics of high energy density capacitors is critical for both the PFN designer and overall weapons system engineering. Aerovox Type LM capacitors (2.4MJ/m3) were evaluated under the projected Navy operating scenarios, including rep-rate and burst modes.

The Aerovox Type LM capacitors, first used in the US Army 8.5 MJ Pulsed Power Module in 1991, are known to be nonlinear with respect to capacitance and voltage. Additionally, the charge/discharge efficiency is known to be lower for this capacitor than for other, lower energy density capacitors. The life characteristics of the capacitor have been established under normal operating conditions. This paper discusses the performance of the Aerovox Type LM capacitors in both normal and fault mode conditions. The parameters discussed include temperature variations, voltage reversal, and peak current performance. Thermal stability and fault mode performance for the capacitor is also defined.

INTRODUCTION

The application of capacitors for shipboard ETC guns necessitate a number of specific capacitor requirements. The specification includes:

- A life expectancy of 1000 Shots with reliable (predictable) life characteristics
- Compact size
- The ability to operate in the burst mode <100 shots
- Thermal stability with or without cooling during burst mode operation
- Energy efficiency of >60%
- The ability to survive faults with high peak current or high voltage reversal

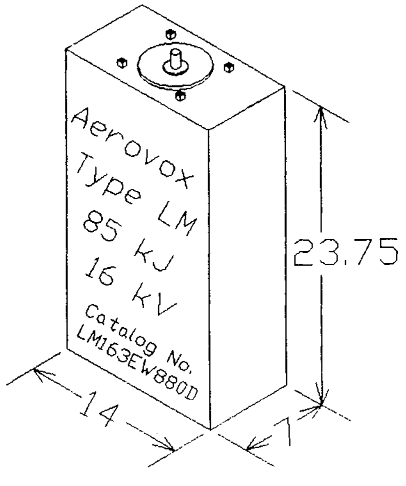

Figure 1

Aerovox Capacitor PN LM163EW880D02A Performance Characteristics			
Electrical		Mechanical	
Item	Rating	Item	Rating
Voltage	16 kV	Dimensions	
Capacitance	880 uF	Length	13 In.
Delivered		Width	7 In.
Energy	85 kJ	Height	23.75 In.
Life	1000 Shots	Volume	2161 $In.^3$
ESR	< 20 mΩ		0.0354 m^3
ESL	<100 nH	Weight	61.4 kg
Energy Density	2.40 MJ/m^3	Energy Density	1.4 J/g

Table 1

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The US Navy has been developing ETC gun system technologies since 1990 for use in ship self defense and surface ftre support missions. Emphasis has been placed on the capacitor-based pulse forming network (PFN) as the primary means of energy storage and pulse shaping. Defining and understanding the electrical and mechanical performance characteristics of high energy density capacitors is critical for both the PFN designer and overall weapons system engineering. Aerovox Type LM capacitors (2.4MJ/m3) were evaluated under the projected Navy operating scenarios, including rep-rate and burst modes. The Aerovox Type LM capacitors, ftrst used in the US Army 8.5 MJ Pulsed Power Module in 1991, are known to be nonlinear with respect to capacitance and voltage. Additionally, the charge/discharge efficiency is known to be lower for this capacitor than for other,lower energy density capacitors. The life characteristics of the capacitor have been established under normal operating conditions. This paper discusses the performance of the Aerovox Type LM capacitors in both normal and fault mode conditions. The parameters discussed include temperature variations, voltage reversal, and peak current performance. Thermal stability and fault mode performance for the capacitor is also defined.

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The capacitors in this testing series consisted of 16 kV, 85 kJ capacitors, Aerovox Part Number LM163EW880D02A shown in Figure 1, and small scale capacitors. The small scale capacitors were used to establish performance expectations for the full scale capacitors which were then tested near, but below the established limits. All of the capacitors used in the test series were made with the same dielectric and electrode system. In the dielectric system, the majority of the energy is stored in polyvinylidene fluoride (PVDF) film. The electrodes are self clearing metallized electrodes.

The data presented here has been normalized so that both the large and small scale data can be compared directly. The rating of the full scale capacitor under evaluation is shown in Table 1. The small scale capacitors were less than 1% of the size of the full scale capacitors.

METALLIZED ELECTRODE CAPACITORS

There are a number of advantages associated with the use of metallized electrode capacitors. Since the capacitors are self healing [1,2,4], the result of a dielectric breakdown is a very small loss of capacitance rather than a shorted capacitor. The end of life for the Type LM capacitors is not a short circuit and the resultant energy dump, but the slow loss of capacitance. The rate at which a metallized capacitor is failing can be tracked by monitoring the rate of capacitance change. End of life is normally defined as the loss of 5% of the initial capacitance. The capacitance loss is an accumulation of thousands of clearing sites each resulting in a slight loss of capacitance.

LIFE EXPECTANCY

Figure 2 is a curve showing the capacitance loss vs. cycles for a full scale capacitor operating under normal discharge conditions with a 25 second charge time, 12,000 amp output current and 10% voltage reversal. When the capacitor is charged, the physical forces constricting the dielectric cause the capacitance to increase. For the capacitor shown, the initial increase was 12%. After some 80 shots, the capacitor was allowed to rest overnight. The capacitance in the morning was 2.5% above the initial capacitance.

The life characteristics of Figure 2 are typical of capacitors discharging at 1 Hz or less into a ETC load with an internal temperature that is less than 55°C. Operating the capacitors at temperatures above 75°C and faster than 4 Hz will cause a significant increase in capacitance loss.

In an effort to minimize the effect of the shift in capacitance with use, all the capacitors were all brought to the same charge history before tests were run. All of the capacitors used in the testing series were preconditioned by charging and discharging the capacitors and then letting them sit overnight with the terminals shorted before initiating the tests discussed below.

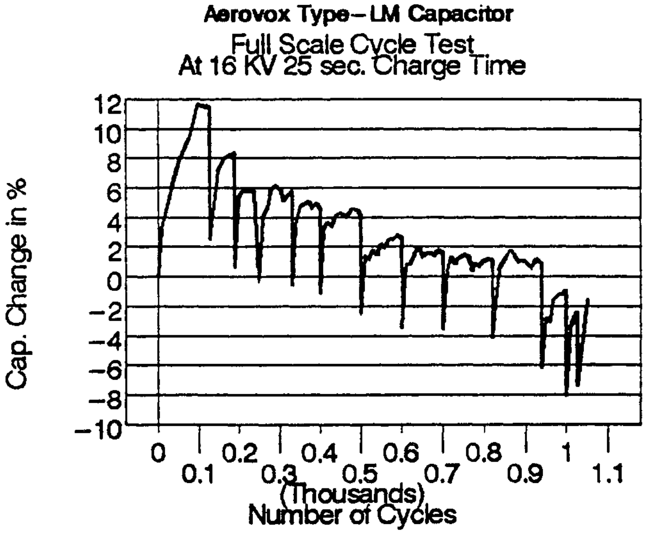

Figure 2

CHARGING PROFILE

The Aerovox Type LM capacitor require more energy on the first shot than subsequent shots in burst mode operation. Some of the energy is used to change the dielectric and increase the capacitance of the unit while other energy is permanently lost in the form of heat. The testing series attempted to determine the charge profiles of the capacitors under various operation conditions.

Small scale capacitors were tested at rep-rates of 0.07 Hz, 1 Hz and 4 Hz over a temperature range of 10°C to 55°C. Then a full size 85 kJ capacitor was tested at 25 deg.C. The capacitors in this test series were charged with a "constant current" power supply. The voltage and current for the charge and discharge cycles were monitored. Typical results are shown in Figures 3, 4 & 5.

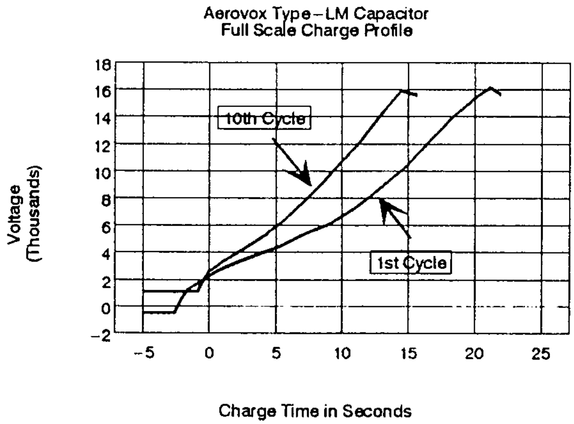

Figure 3

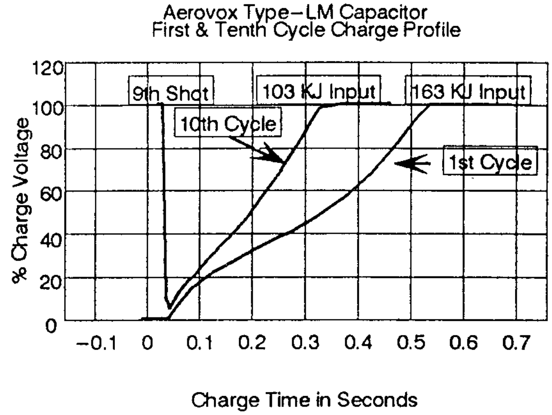

Figure 4

The nonlinear charge voltage profile dubbed the "swayback" charging curve is a result of the nonlinear characteristics of the capacitor and was evident throughout the test series. The effect of retained charge on the charging cycle can be observed by comparing the time required to charge during the first and tenth charge cycle in Figure 3 & 4. Typically it will take 37% less energy and 45% less time to charge the capacitors the tenth time than the first time when charging the capacitors in the 5 second range. The difference is less pronounced if the capacitors are charged in the 15 second range as were the full sized capacitors of Figure 4.

The operating temperature had little effect on the charging profile of the capacitors as shown in Figure 5. During the test series, the data at 10°C and 25°C was essentially identical. The charge time at 55°C was consistently longer than at the lower temperatures by about 5%.

DISCHARGE ENERGY

A typical discharge under normal operating conditions is shown in Figure 6. The voltage and current for each set of data points are multiplied together and then summed to determine the energy delivered by the capacitor. For Aerovox capacitors, the delivered energy is the rated energy of the capacitor. There was no measurable difference in the discharge waveform from any of the capacitors tested that was associated with the variations in the charging profile, operating temperature, or repetition rate over the ranges tested.

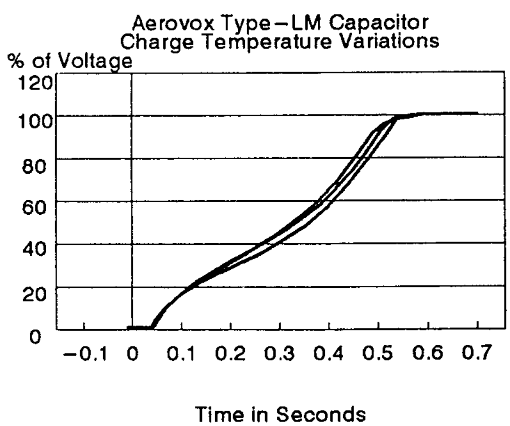

Figure 5

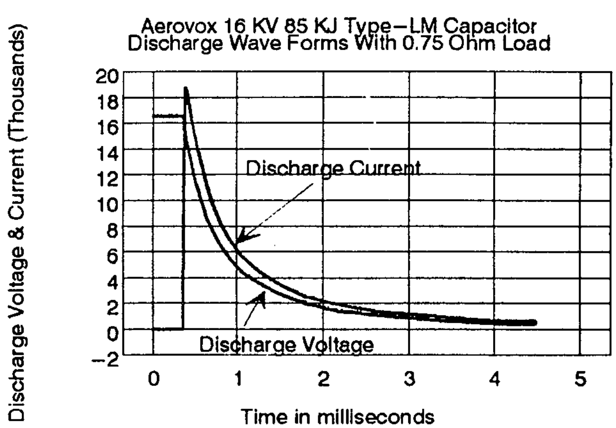

Figure 6

INTERNAL HEAT RISE

During the testing series, the temperature rise was measured on a number of capacitors. The most useful information came from small scale capacitors that were built with internal thermo-couples. Typical results are shown in Figure 7 where capacitors were run through 30 cycles starting at 10 °C and 55°C. The fast rise on the first few cycles is characteristic of this type of capacitor. After this, the rate of rise slows down. The capacitor running at 55°C had a total temperature rise that was 5°C higher than the capacitor that started at 25°C. This is consistent with the longer charging time at the higher temperature. The test shows that a capacitor starting at 55°C is thermally stable for 30 shots. Also, the capacitor can be operated with an internal temperature of 75°C.

Capacitors were tested with different charge times and different load impedances. Charge times in the 5 to 15 second range had little effect on the internal heat rise. It was found, however, that decreasing the load resistance by an order of magnitude increased the internal temperature rise by 5°C in a 30 shot burst. The data shows that for the ETC gun load, the capacitors would be thermally stable for a 100 shot burst if the capacitors' initial temperature is about 15°C.

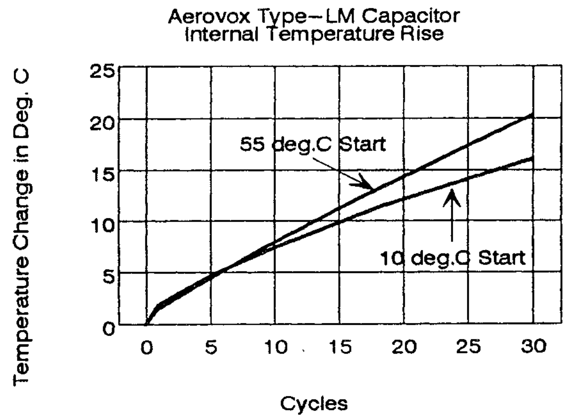

Figure 7

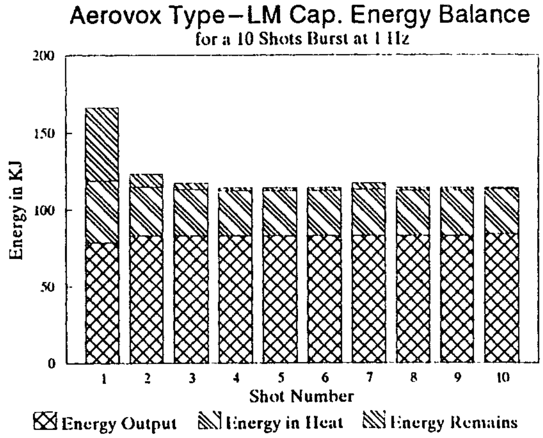

Figure 8

ENERGY BALANCE

Two of the questions that were addressed during the test series were "how efficient are the capacitors?" and "where does the energy go?". The energy not released during the duration of discharge pulse is lost in the form of heat or retained in the capacitor. The energy balance will be defined as the total energy required to charge the capacitor equaling the summation of the energy delivered during discharge, plus the energy loss in the form of heat and the energy retained in the capacitor. Figure 8 Shows a typical burst of 10 shots run at 1 Hz where both the input energy and the output energy are shown. The heat energy is calculated based on the internal temperature rise and the specific heat of the capacitor. The energy that was not accounted for as discharge energy or heat is shown as retained energy. The output energy was consistent except for the first shot where the charge voltage was slightly below the test voltage.

The input energy on the first shot is twice the output energy with about one quarter turned into heat and one quarter retained by the capacitor. For the preconditioning mentioned earlier, the first cycle efficiency was 47%. By the third cycle, the efficiency was up to 65% and approaching 70%on the 10th cycle.

FAULT CURRENT

The performance of the capacitor under fault conditions was of concern. This was evaluated by taking small scale capacitors through increasingly higher fault shots. The results shown in Figure 9 indicate that the capacitors will withstand occasional 200 kA discharges with minor degradation. The maximum anticipated fault for the ETC gun application was 80,000 amps. The full scale capacitor of Figure 10 was tested at this level.

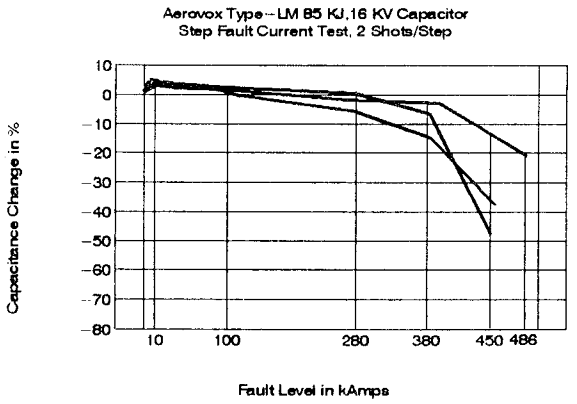

Figure 9

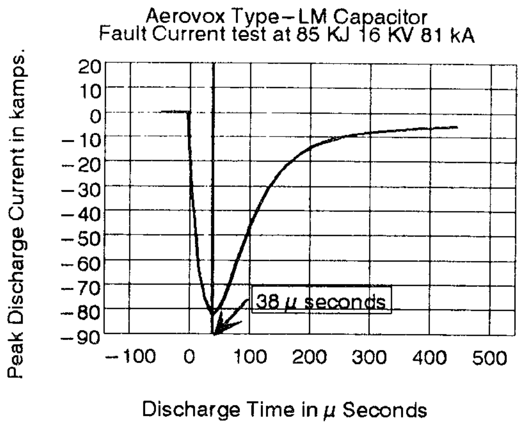

Figure 10

FAULT REVERSALS

Perhaps the most interesting discovery of the test series was the capacitors' performance under high reversal fault conditions. Small scale capacitors were tested on circuits that were expected to deliver 10% to 90% voltage reversal. In all cases, the actual voltage reversal was less that than anticipated based on linear calculations as shown in Figure 11.

The relationship between the voltage across the capacitor and the current through the capacitor on a calculated 90% reversal circuit is shown in Figure 12. During the discharge, the nonlinear characteristic of the Type LM capacitors show up as an unusual relationship between the current and voltage. The current zeros do not occur at voltage peaks nor do voltage zeros occur at current peaks.

The nonlinear suppression of voltage reversal and the nonlinear charging voltage appear to be the result of the same phenomenon. Under no conditions was a voltage reversal greater that 30% observed.

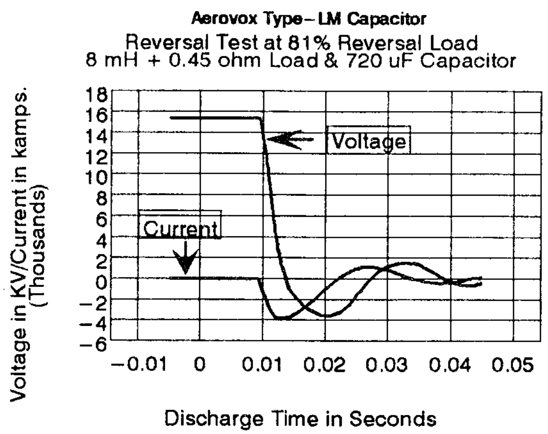

Figure 11

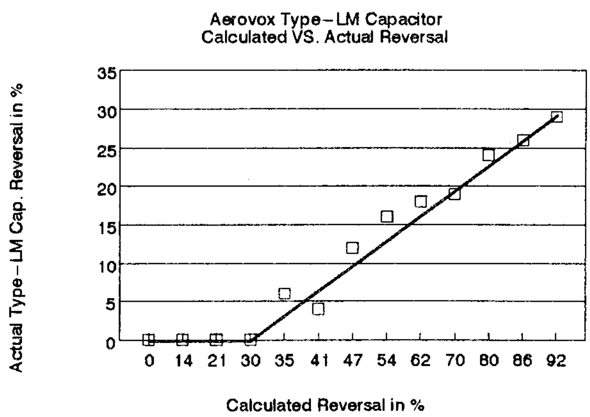

Figure 12

CONCLUSIONS

Aerovox Type LM capacitors are capable of meeting all of the requirements the ET gun application at an energy density of 2.4 MJ/m3 for a 1000 shots capacitor. The capacitors will be thermally stable when operating in a 100 shot burst mode at 1 Hz or less if the initial temperature is in the 10°C to 15°C. The capacitor is capable of operating at an internal temperature of 75°C.

The capacitors will withstand the 80,000 amp worst case anticipated system fault without damage. The limit on fault current for this capacitor is about 200,000 amps where the capacitor would sustain measurable damage. Likewise, the capacitor will withstand voltage reversals that are caused by the energy in the capacitor resonating with the system without damage. When the capacitor was discharged into a 90% reversal circuit, the maximum reversal is less than 30%. No measurable damage was done to the capacitor as a result of this type of this duty. The suppression of reversal is seen as an advantage for the entire PFN..

REFERENCES

[1] High Energy Density Pulsed Power Caps - presented at the Advanced Pulsed Power Conference - Albuquerque NM, August 1, 1990.

[2] The Impact of Metallized Electrodes on High Energy Density Pulse Power Capacitors - presented at the 13th Capacitor and Resistor Technology Symposium, CARTS '93 - Costa Mesa CA, March 10, 1993

[3] The Impact of High Energy Density Capacitors with Metallized Electrode in Large Capacitor Banks for nuclear Fusion Applications - Presented at the 9th IEEE Pulsed Power Conference - Albuquerque NM, June 22, 1993.

[4] Feuerstellung 2000: Characteristics and Performance of High Energy Density Capacitors Applied in the 30 MJ Pulsed Power Supply System - Presented at the 5th European Symposium on Electromagnetic Launch Technology - Toulouse France, April 10, 1995.